Viewgraphs from May 13, 2005 meeting in order of presentation

Review of Key Items

- TMA bullet items:
  - Mirror Design/Configuration
  - Trailer Gap/Side/Wake Treatments (gap closure, side enclosure, trailer wake
  - Trailer Aero/Gap Enclosure/Gap Flow Control
  - Vehicle Underside Airflow/Thermal Control
  - TMA Truck Test Day -- Opportunity to demonstrate technologies? Do we have to wait for final report to see the results?!?!?
- OEMs have a need to sanitize data, but they must do it such that discoveries are shared and resources are known
- Over-arching critique/comment

  We are too isolated. We need to work together. In order to grow and improve, we need to share and not have everyone "re-inventing the wheel."

1

Review of Key Items

- We should report ΔC_D's instead of percent drag reduction.
- Need to consider underhood/underbody, open radiator, etc. especially as we move to higher fidelity models.
  - Do we have enough information (BC's, validation data, etc.) to make CFD including these complications believable?
- End-user interaction needs to be "stepped up." Put users "in the middle" so that the people at the R&D end are aware of access, maintenance and liability issues.
  - Industry must offer some guidance.
  - As a federal research agency, we have an obligation to show what *can* be done, not just what is feasible in the near-term.
- Have we considered every possible device? Every feasible device?
- Sid likes Hula skirts (non-monolithic skirts)

2

Review of Key Items

- **WE NEED TO GET OUR DEVICES ON THE ROAD**
  - **We've done enough research to make this a reality. It's time to enter the development cycle and get things like skirts, splitter plates, etc. manufactured and used. We've got NorCan onboard. We need more.**
- **Product Engineering**
- **"Honest Broker" ?**
- **Marketing, marketing, marketing, marketing.**

3

Open Questions

4

Issues involving add-ons in general and base flaps in particular

It's time for over-the-road, fleet operation testing.

Tractor manufacturers have not been very supportive. They will always resist change.

The business is entirely customer driven, so deal directly with the operators, such as US Xpress/Wall-Mart?/ UPS?/Schneider?

Can we offer funding support or other inducements? Point out that they could use flaps for fuel-friendly, green-house gas-friendly advertising.

Should we have something waiting in the wings if oil production falls precipitously (Ray Smith's comment)?

What about using the top flap as a brake?

Alec Wong wondered how well the two side flaps alone would work. Good selling point, he said. Should we ask Kevin to test it?

Hybrid truck

Low drag has an even larger payoff since less aerodynamic drag means more kinetic energy recovery with use of motor braking.

$\Delta(KE) \sim MVdV$. It is not so clear whether small speed changes at high speed (truck on highway) would add to more saving than large speed changes at low speed (around-town in traffic).

Quantify savings for hybrid truck for different driving cycles (EPA-Highway or EPA-Town or other). See paper presented at SAE World Congress in April 2005 by Gino Sovran and Dwight Blase (sp??).

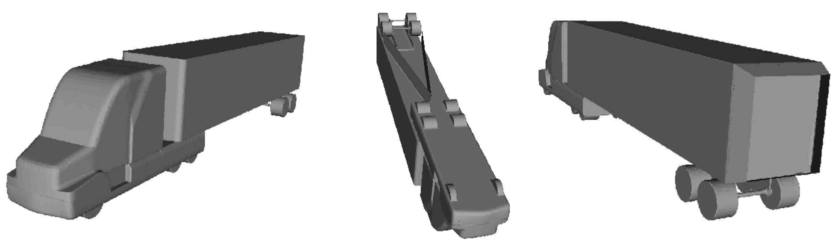
Evaluation of Drag Reduction Devices Using Modeling and Simulation

Jason Ortega

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. UCRL-PRES-212223.

Drag Reduction Devices to be Tested



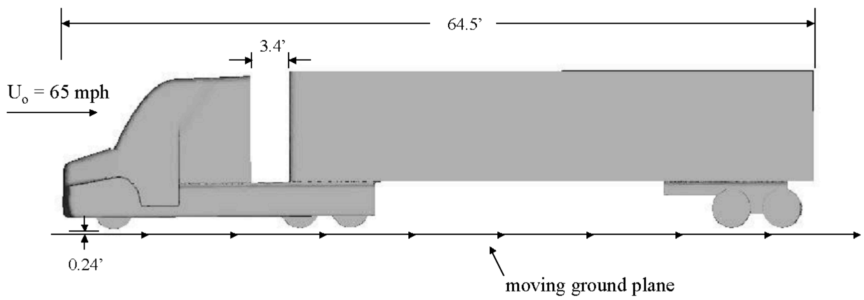
Baseline   Long Wedge Skirt   Base Flaps

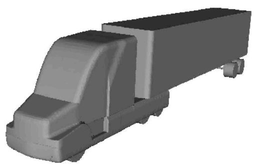
Questions to be Addressed by Numerical Simulations

- How does flow unsteadiness affect device performance?
- How do rotating wheels influence the performance of the base flaps?
- Will the wedge skirt function at realistic Reynolds numbers with more realistic boundary conditions?
- How do the devices modify the flow field about the GCM?
- Can we further optimize the drag reduction devices to be more effective and less intrusive?

Computational Setup

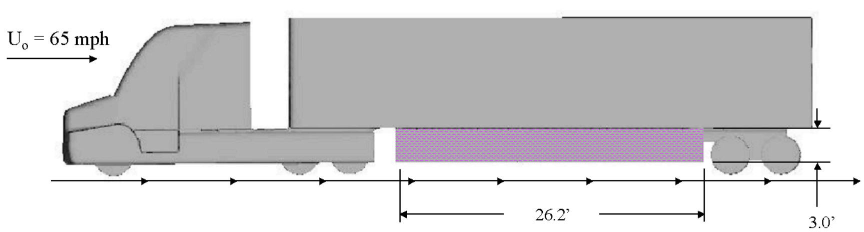
Full-Scale Baseline GCM

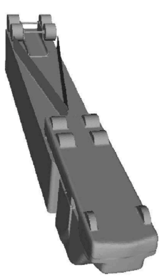




- Full-scale GCM geometry
- $Re_w = U_o w/\nu = 5.02\times10^6$
- Moving ground plane beneath vehicle
- Grid resolution: 5.6×10^6 elements
- STAR-CD CFD code
- Steady RANS simulation
- kω-SST turbulence model with wall functions

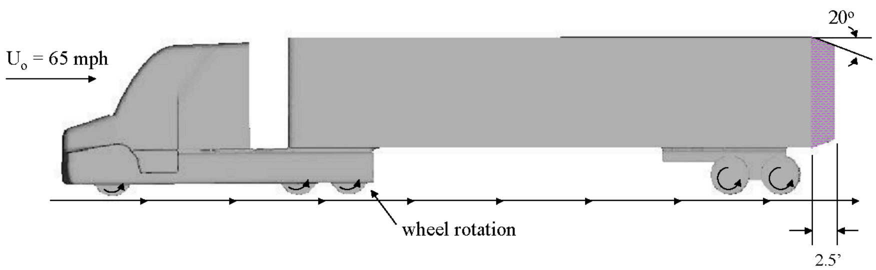
Baseline GCM with Long Wedge Skirt

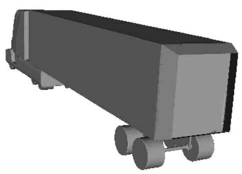




- Grid resolution: 5.6×10^6 elements
- Steady RANS simulation
- kω-SST turbulence model with wall functions

Baseline GCM with Base Flaps

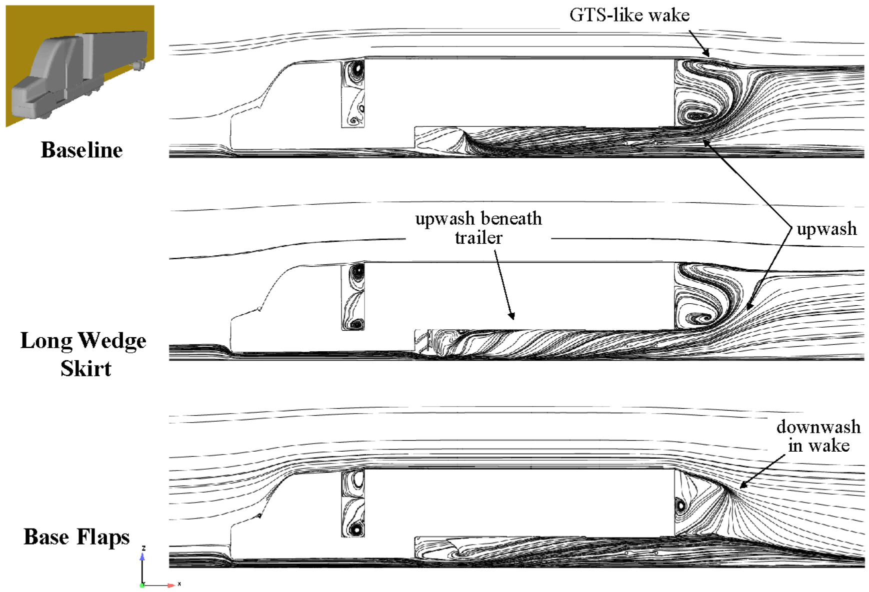




- Grid resolution: 1.5×10^6 (unsteady) and 6.0×10^6 (steady) elements
- Unsteady RANS simulations with and without wheel rotation
- kω-SST turbulence model with wall functions

Results

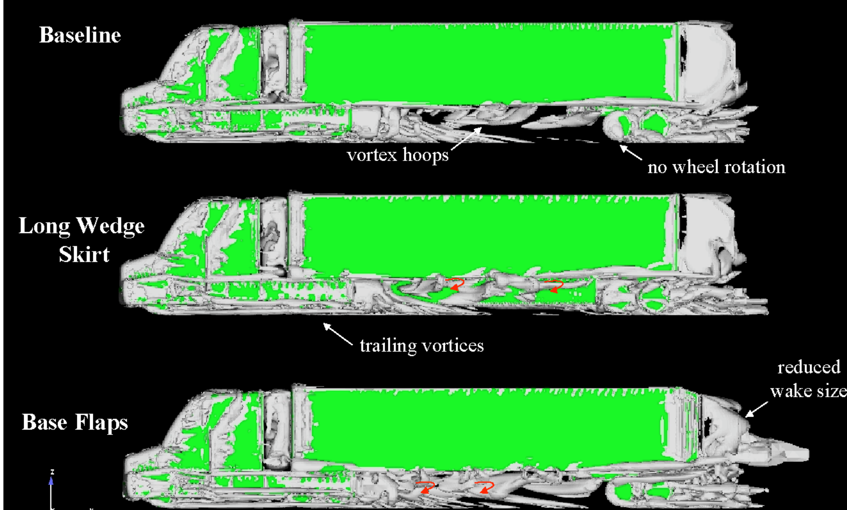
Streamlines for Steady RANS Simulations



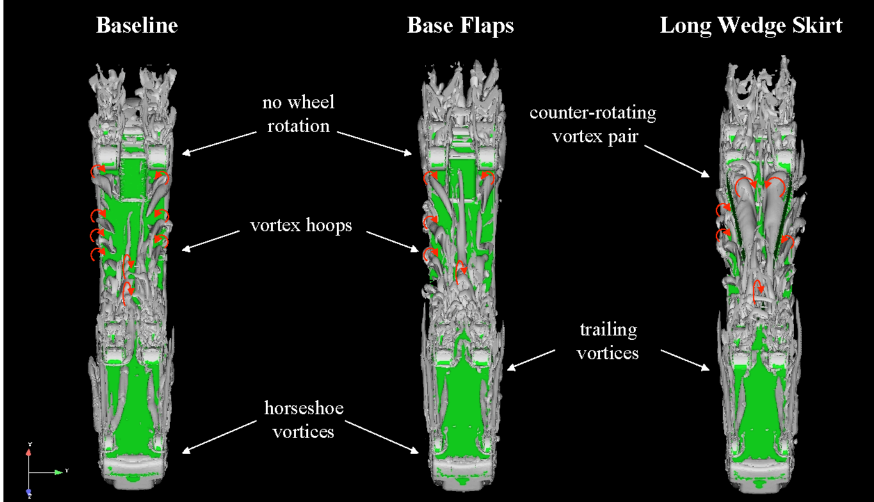
Iso-Q Surfaces Highlight Coherent 3-D Flow Structures

Large, positive values of Q identify regions of the flow dominated by rotational motion

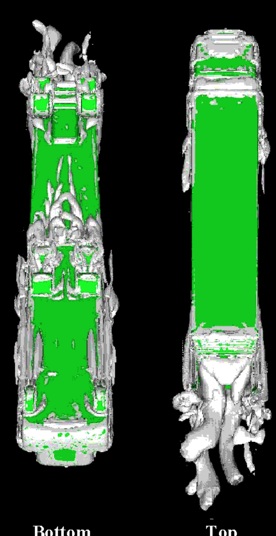
$Q = \_(\Omega\otimes\Omega - S\otimes S)$, (Perry & Chong, 1994; Blackburn *et al.*, 1996; Dubief & Delcayre, 2000)



Iso-Q Surfaces Highlight Coherent 3-D Flow Structures



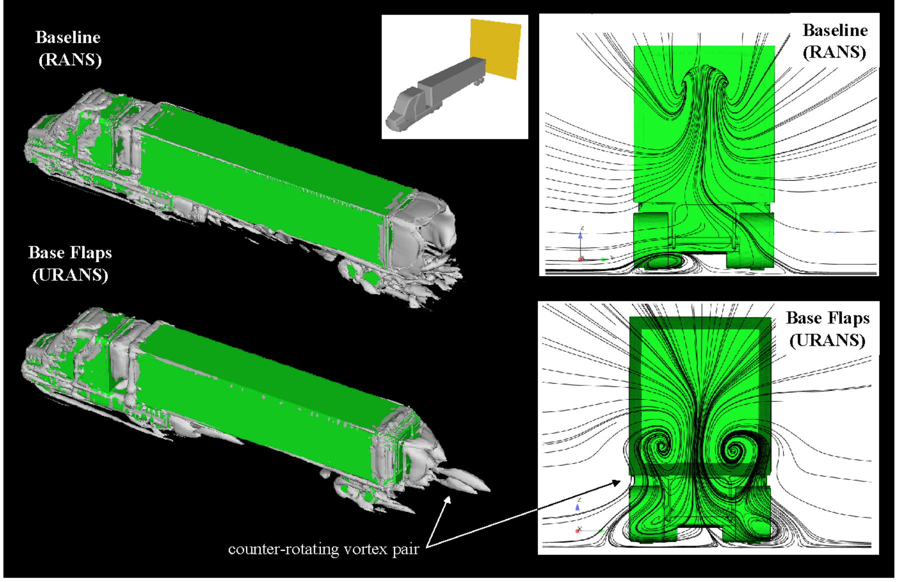
Iso-Q Surfaces for Unsteady RANS Simulations



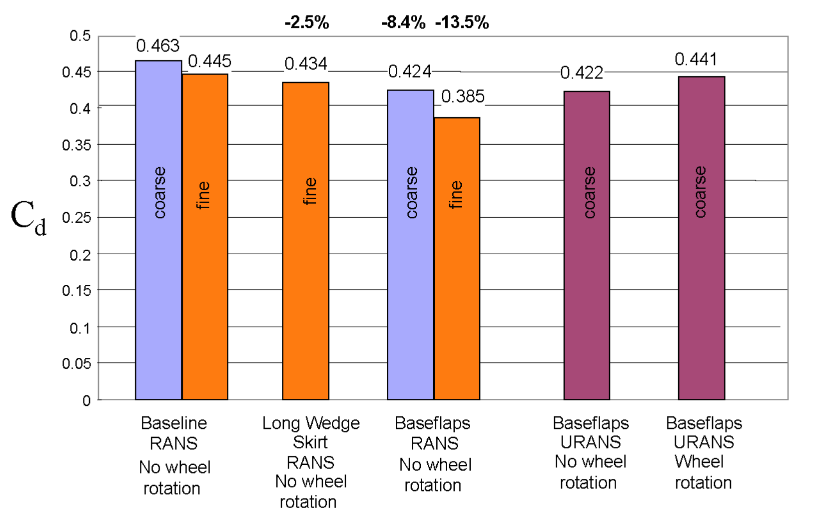
- Base flaps with wheel rotation
- Grid resolution: 1.5×10^6 elements
- $k\omega$–SST turbulence model with wall functions

- URANS highlights the complex, unsteady, 3-D nature of the flowfield about the GCM
- Significant flow unsteadiness on the GCM underside from the tractor base, tractor wheels, and trailer wheels
- Large scale flow structures present in the GCM wake

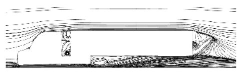
Base Flaps Modify the Flow field by Generating a Counter-Rotating Vortex Pair in the GCM Wake

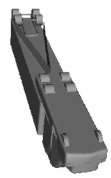


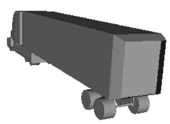
Influence of Drag Reduction Devices and Wheel Rotation on C_d

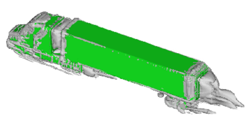


Summary



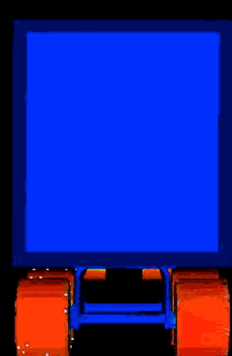




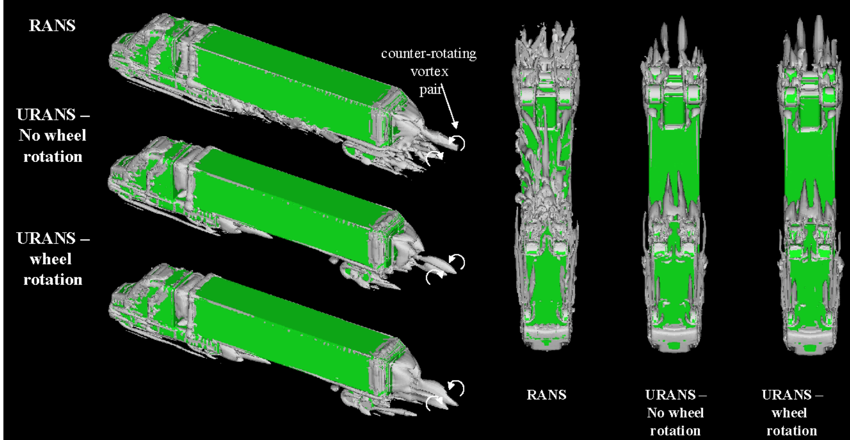


- How does flow unsteadiness affect device performance?
  - $C_{d\ RANS} \approx C_{d\ URANS}$ for the base flaps configuration at 0° yaw
- How do rotating wheels influence the performance of the base flaps?
  - $C_{d\ rotating} > C_{d\ non\text{-}rotating}$
- Will the wedge skirt function at realistic Reynolds numbers with more realistic boundary conditions?
  - $\Delta C_d/C_d \approx 2.5\%$ at 0° yaw
- How do the devices modify the flow field about the GCM?
  - Base flaps generate downwash and a counter-rotating vortex pair in the GCM wake
  - Long wedge skirt generates upwash beneath the trailer by means of a counter-rotating vortex pair
- Can we further optimize the drag reduction devices to be more effective and less intrusive?
- Steady RANS simulations are inadequate to fully understand the complex, 3-D evolution of the flow field about the GCM

Time-Averaged URANS: Base Flaps with Wheel Rotation



Iso-Q Surfaces: RANS & Time-Averaged URANS

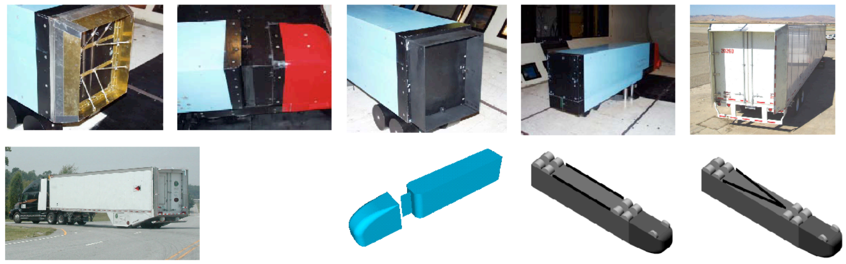


- Significant difference between the underside flow of the RANS results and the time-averaged URANS results
- All three base flaps cases demonstrate a counter-rotating vortex pair in the wake of the GCM
- Wheel rotation slightly changes the wake structure

Overview

- Motivation and Background
- Computational Setup
- Results
- Conclusions

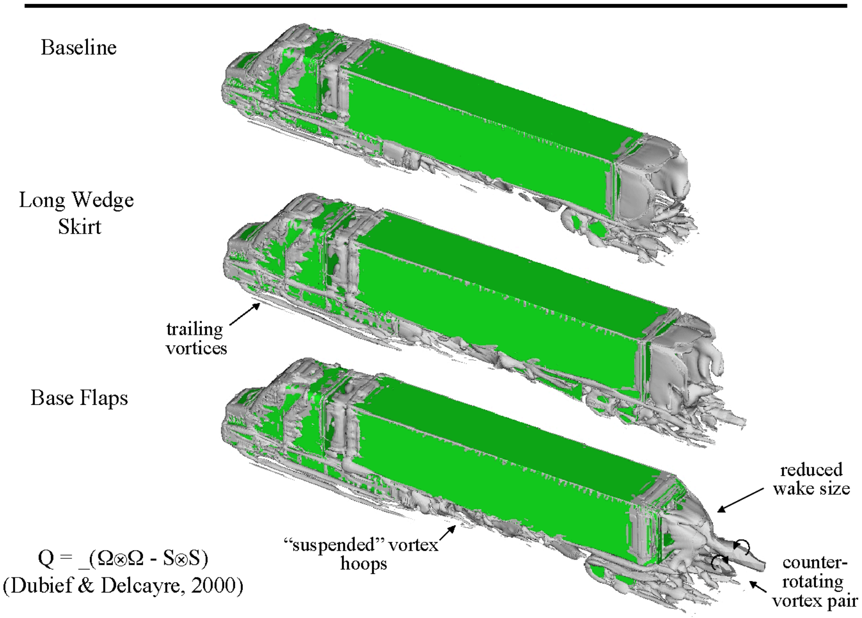
Devices Shown to Provide Drag Reduction



Percent change in wind-averaged drag coefficient/
Fuel Economy

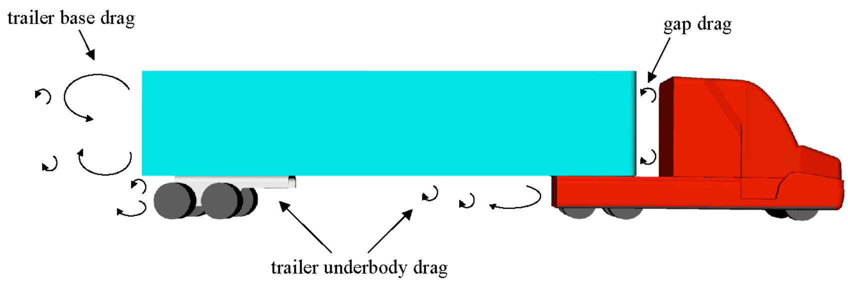
Device	NASA	USC	GTRI	LLNL
Side Extenders	37%	———	———	———
Gap Splitter Plate		n/a	———	———
Boattail Plates	13.7%	———	———	8.8%
Base Flaps	19.4% (20)	**~ 4.15% (13)**	———	16.4% (10)
Straight Side Skirts	6.5%	———	———	1.4%
Long Wedge Skirt	———	———	———	2.1%
Low Boy	11.8%	———	———	———
PHV	———	———	**~ 4-12%**	———

Iso-Q Surfaces for Steady RANS Simulations



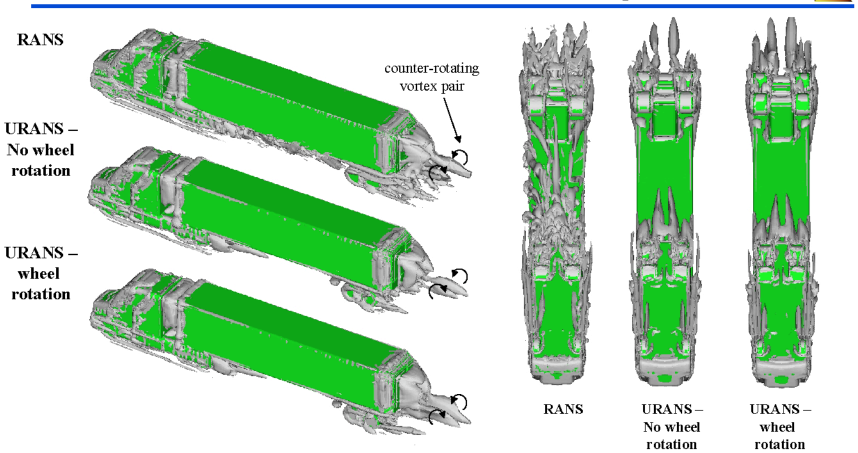
Q = _(Ω⊗Ω - S⊗S)
(Dubief & Delcayre, 2000)

Major Sources of Aerodynamic Drag



- Cross-stream flow in the tractor/trailer gap
- Trailer underbody drag due to flow separation off of tractor underside and flow impingement on trailer wheels
- Separated flow off of the trailer base

Iso-Q Surfaces: RANS & Time-Averaged URANS



- Significant difference between the underside flow of the RANS results and the time-averaged URANS results
- All three base flaps cases demonstrate a counter-rotating vortex pair in the wake of the GCM
- Wheel rotation slightly changes the wake structure

Computational Simulation of Tractor-Trailer Gap Flow with Aerodynamic Devices

Paul J. Castellucci

Kambiz Salari

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

May 13, 2005

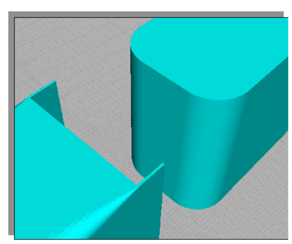
Lawrence Livermore National Laboratory

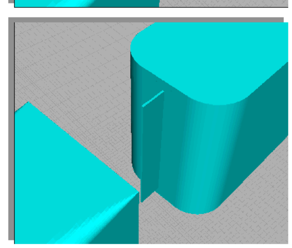
UCRL-PRES-212230

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Gap Flow Simulations of the M-GTS are Chosen For Experimental Comparison

- Simulations are performed with both tractor cab extenders and single trailer splitter plates (approx 20").
- Each device is tested at 6° yaw and non-dimensional gap lengths of 0.35 and 0.65 (approx 3' – 6').
- USC has compiled body force and PIV data of the Modified Ground Transportation System (M-GTS) at Reynolds number 340,000.

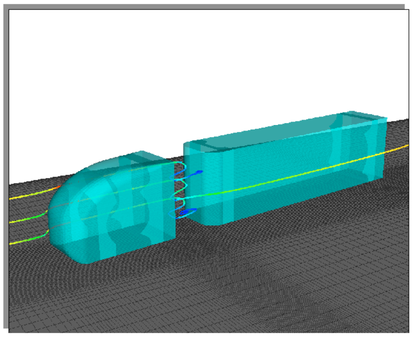




DOE 51305-2

Gap Flow Simulations of the M-GTS are Chosen For Experimental Comparison

- Simulations are performed using NASA's OVERFLOW; a compressible, control-volume based, Navier-Stokes code using overset grids.
- Based on prior GTS simulations, all cases are run with Menter-SST steady RANS turbulence model.
- A moving ground plane boundary condition is employed to mimic experimental conditions.

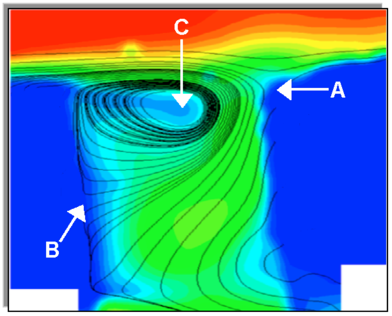


Baseline M-GTS at 6° yaw

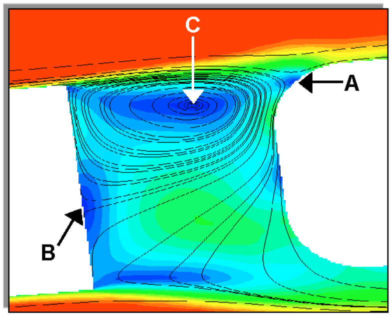
DOE 51305-3

Baseline Simulations Capture Qualitative Gap Flow Features

Baseline M-GTS Streamlines and Velocity Magnitude Contours



Experiment at 6° Yaw and 0.65 Gap (Browand)



Simulation at 6° Yaw and 0.65 Gap

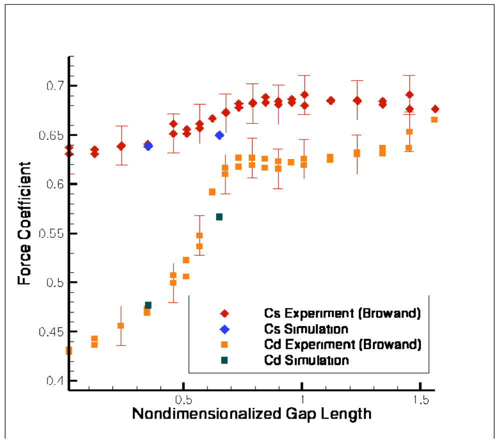
- Stagnation points (A, B) and vortex core (C) are similar to PIV data.
- Flow velocities are comparable, yet consistently lower than experiment.

DOE 51305-4

Baseline M-GTS Body Forces Compare Favorably to Experimental Data

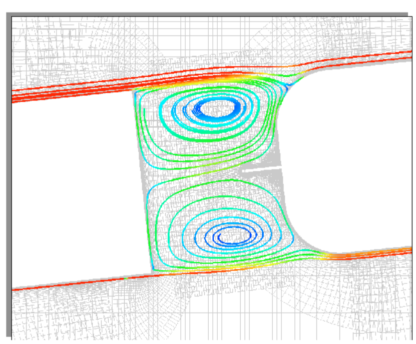
- Computed drag and side force coefficients are within experimental uncertainty.
- Baseline simulations capture rapid drag rise at larger gap lengths.

M-GTS Body Force Coefficients at 6° Yaw



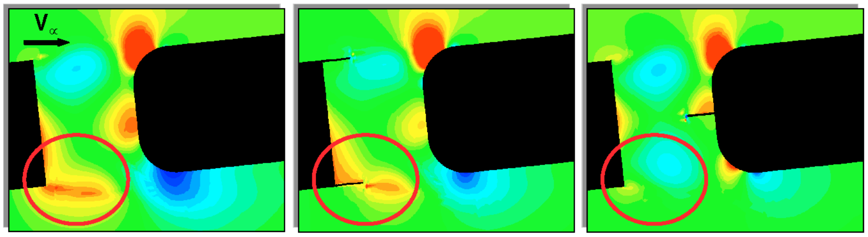
Simulated Devices Reduce Drag Through Two Primary Mechanisms

- Simulated devices decrease drag by:
  1) Reducing gap cross-flow
  2) Increasing tractor base pressure
- Tractor cab extenders realign the primary horseshoe vortex in the tractor-trailer gap.
- Trailer splitter plates creates a nearly-symmetric dual recirculation.
- The trailer splitter plate is more effective than cab extenders in reducing drag while maintaining side force.



Streamtraces colored by velocity magnitude

Both Aerodynamic Devices Decrease Tractor Drag and Increase Side Force

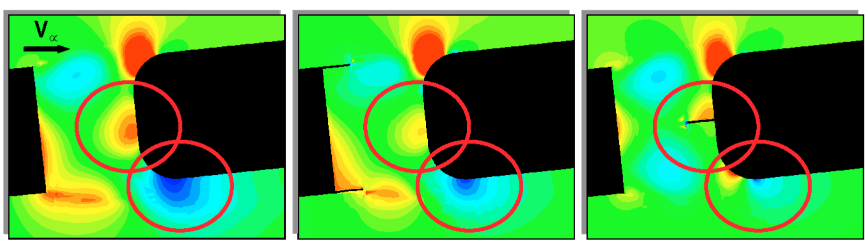


Pressure at 6° yaw and 0.65 gap

- **Trailer splitter plates and tractor cab extenders decrease gap cross-flow by 30% and 50%**
- **Flow directed at the tractor base, increases pressure and decreases drag.**
- **Less cross-flow stagnates against the leeward shear layer, increasing tractor side force**

DOE 51305-7

Both Aerodynamic Devices Decrease Trailer Drag and Side Force

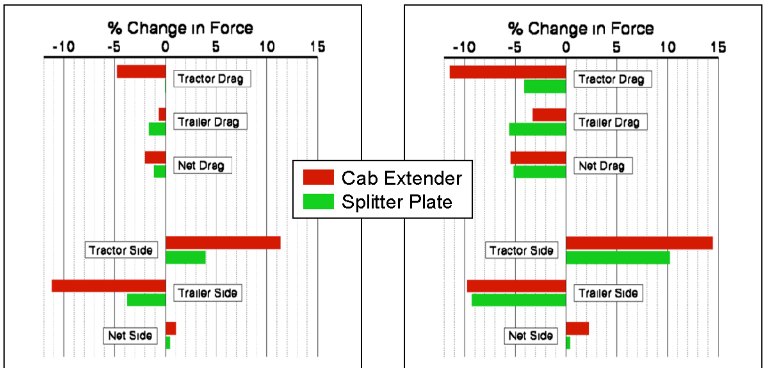


Pressure at 6° yaw and 0.65 gap

- **Trailer splitter plates and tractor cab extenders decrease gap cross-flow by 30% and 50%**
- **Less flow impacts the trailer face, reducing pressure.**
- **The leeward shear layer is deflected less, resulting in higher pressures on the trailer side.**

DOE 51305-8

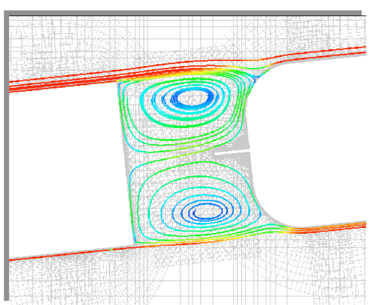
The Trailer Splitter Plate is Effective at Reducing Drag at Low Reynolds Numbers



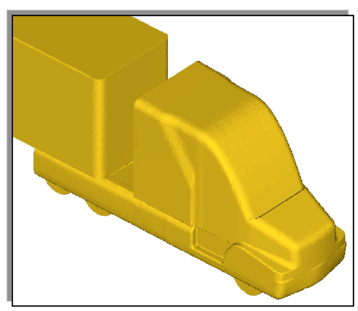
M-GTS with 0.35 length gap   M-GTS with 0.65 length gap

- The trailer splitter plate is nearly as effective as tractor cab extenders in reducing total vehicle drag, without a significant increase in side force.

Extension to Full-Scale Reynolds Numbers Raises Additional Questions

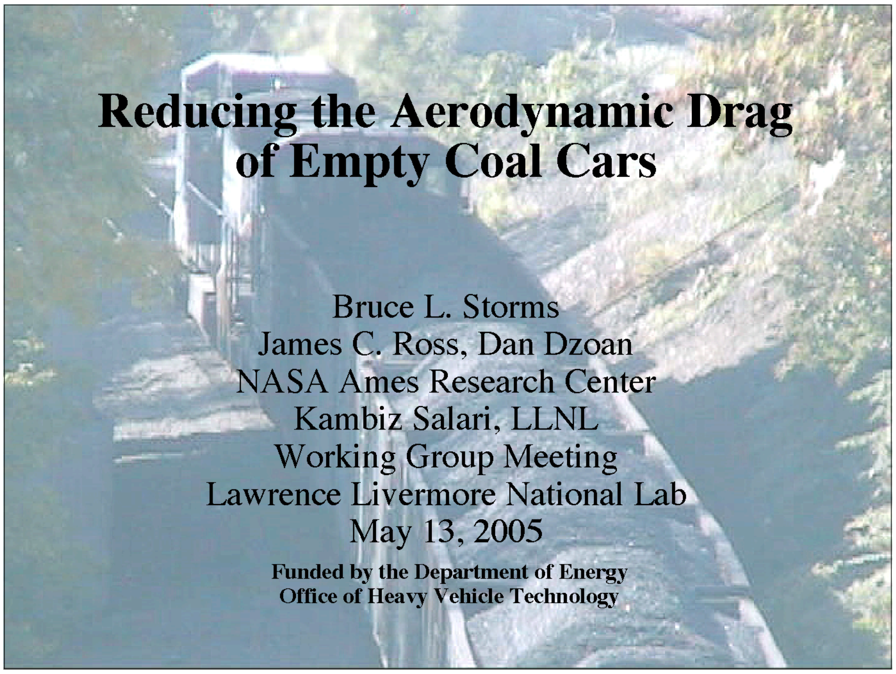


Modified Ground Transportation System



Generic Conventional Model (GCM)

- It is unclear if the large radii of the trailer leading edges will affect the performance of the aerodynamic devices.
- The 3-D effects of an open gap-underside may be exacerbated at higher Reynolds numbers.



Reducing the Aerodynamic Drag of Empty Coal Cars

Bruce L. Storms
James C. Ross, Dan Dzoan
NASA Ames Research Center
Kambiz Salari, LLNL
Working Group Meeting
Lawrence Livermore National Lab
May 13, 2005

Funded by the Department of Energy
Office of Heavy Vehicle Technology

Outline

- Background
- Facility & Model
- Test Details
- Results
- Summary

Background

- 2002 U.S. Statistics*
  - Coal provided 50% electricity
  - Total = 1 billion tons, 66% carried by rail
  - 44% tonnage, 25% loads, 21% revenue
  - 85% by unit trains (50+ cars)
  - Avg coal haul = 696 miles
- Aero Drag Reduction Potential
  - Fuel consumption: empty ≈ full
  - Aero drag ~ 15% of round-trip fuel consumption
  - 25% reduction –> 5% fuel savings (75 million gal)

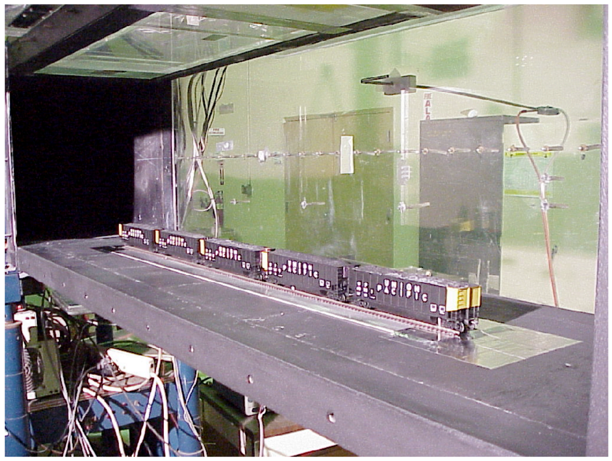
* The Rail Transportation of Coal, AAR, Vol. 5, 2003

Ames Research Center
Experimental Physics Branch

15” x 15” Wind Tunnel

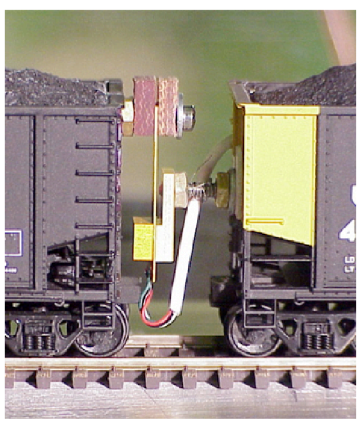
Ames Research Center
Experimental Physics Branch

Model Installation



Experimental Physics Branch

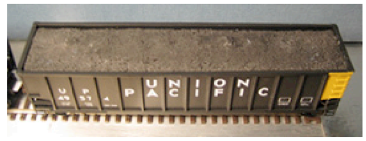
Test Details



- **Drag force measured using 2-lb load cell**
- **Test Conditions**
  - **Velocity = 65 m/s (145 mph)**
  - **Model Reynolds No. = 160,000**
  (full-scale Re = 3.9 million at 40 mph)
  - **Critical Re = 10,000**
- **Yaw angles 0° to 10°**
- **Uncertainty:**
  - **1.0 - 1.5% for yaw ≤ 5°**
  - **2.5 - 4.9% for yaw > 5°**

Experimental Physics Branch

Empty vs Full Cars

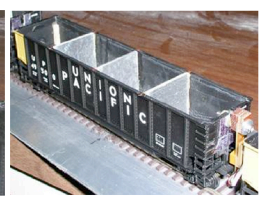
Yaw (ψ, deg)	C_D empty	C_D full	C_R empty	C_R full	% difference (full-empty)
0	0.3334	0.2358	0.0924	0.0653	-29.3
10	0.6015	0.3519	0.1719	0.1006	-41.5

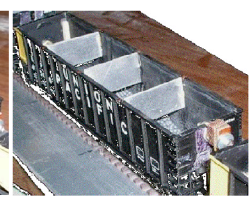
$C_D = D \,/\, q{*}A$ where $q = {}^{1}/_{2}\, \rho U^2$

$C_R = 1.0756\, \rho\, A\, C_D \,/\, \cos^2 \psi$, lb/mph²

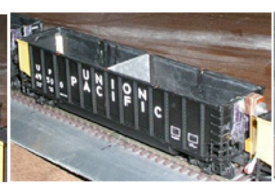
Cover & Divider Configurations

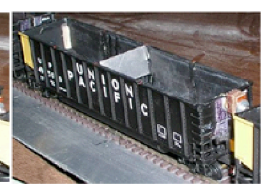

Cargo-bay Cover


3 Full Dividers


3 Half Dividers


Elevated Dividers


Single Full Divider


Single Half Divider

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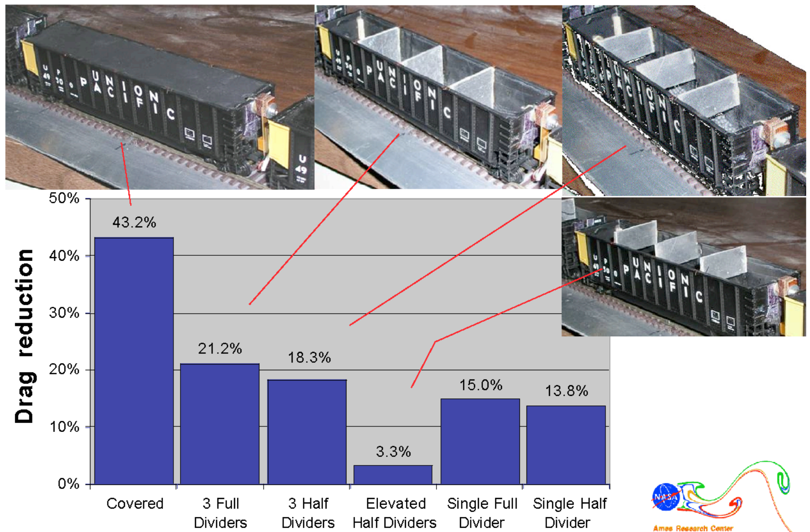
Experimental Physics Branch

Cover & Divider Configurations

($\psi = 0$, no crosswind)



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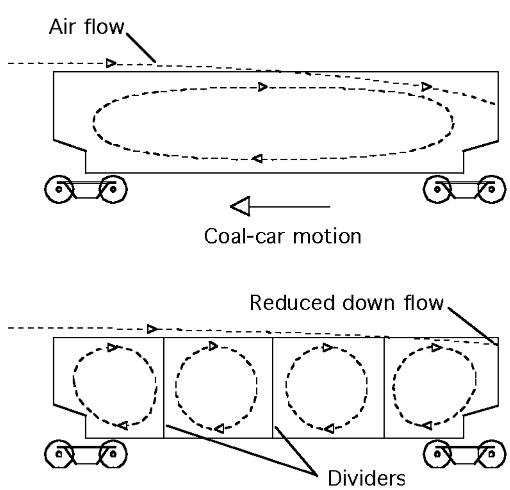
Hypothesized Flow Field



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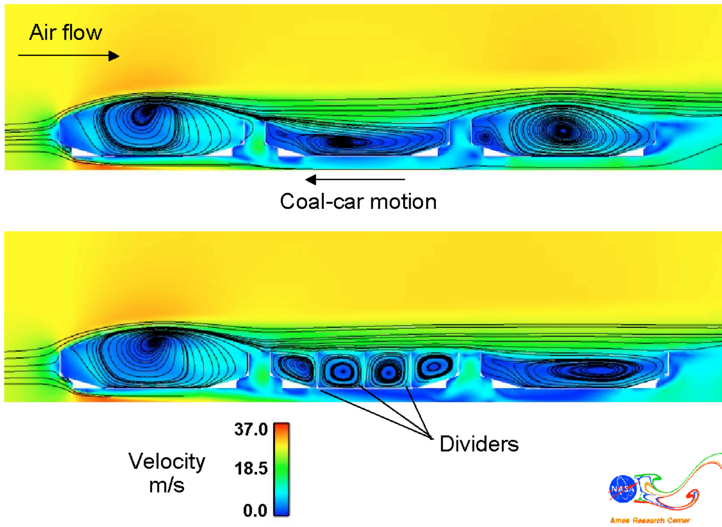
Computed Flow Field



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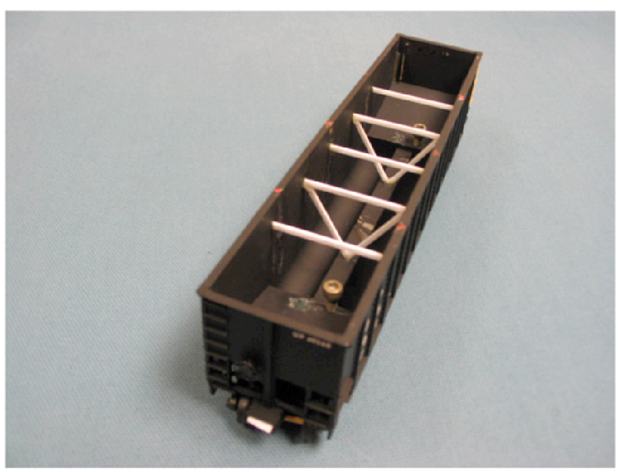
Internal Bracing



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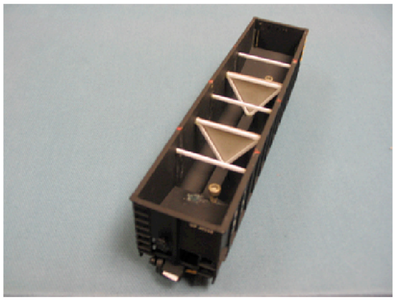
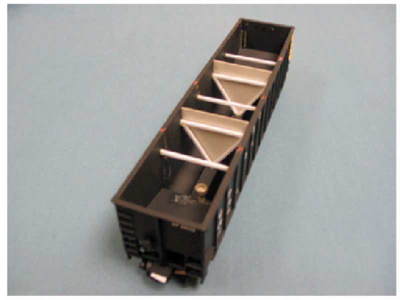
Internal Bracing with Dividers

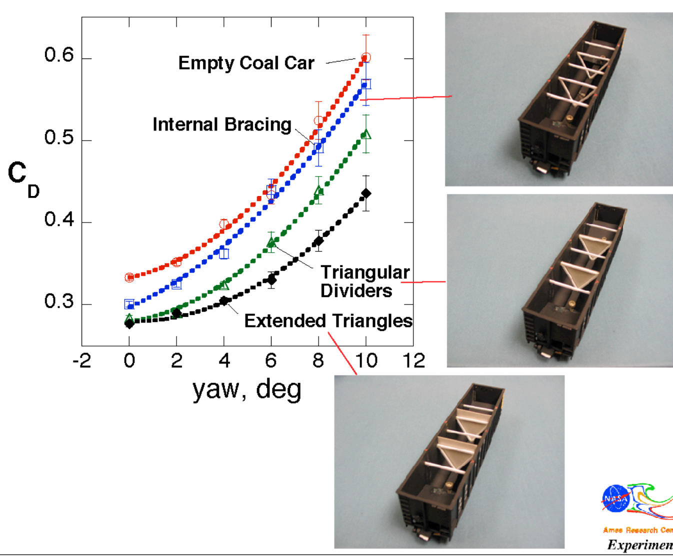


Triangular Dividers

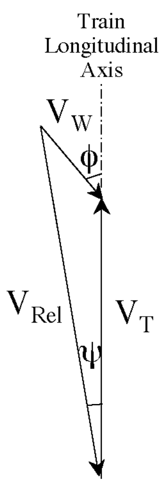


Extended Triangles

Effect of Bracing & Dividers



Wind-Averaged Drag, $\overline{C}_D$



$$\overline{C}_D(V_T) = 1/6 \sum_{j=1}^{6} M(j)\, C_D(j)$$

$$M(j) = 1 + (V_W/V_T)^2 + 2(V_W/V_T)\cos\phi(j)$$

$$\phi(j) = (j \times 30 \text{ deg}) - 15 \text{ deg}$$

$$C_D(j) = C_D \text{ at } \psi(j)$$

$$\psi(j) = \tan^{-1}\left[\frac{(V_W/V_T)\sin\phi_j}{1 + (V_W/V_T)\cos\phi_j}\right]$$

Mean wind speed, V_w = 7 mph

From SAE Recommended Practice, SAE J1252, 1981.

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Wind-Averaged Drag Example

Empty Coal Cars, Train Velocity = 40 mph

j	φ(j), deg	ψ(j), deg	M(j)	Cd(j)	M(j)Cd(j)
1	15	2.2	1.369	0.3569	0.4885
2	45	6.3	1.278	0.4541	0.5804
3	75	9.2	1.121	0.5660	0.6346
4	105	10.0	0.940	0.6057	0.5694
5	135	8.0	0.783	0.5175	0.4053
6	165	3.1	0.693	0.3725	0.2580

$$\overline{C}_D(40 \text{ mph}) = 1/6 \sum_{j=1}^{6} M(j)\, C_D(j) = 0.4894$$

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Wind-Averaged Drag & Resistance

Configuration	$\overline{C}_D$ wind-avgd	% diff	ΔR, lbs 100 cars, 40 mph
Empty	0.4894	0.0	0.0
Internal Bracing	0.4638	-5.2	-1133
Triangular Dividers	0.4118	-15.8	-3443
Extended Triangles	0.3661	-25.2	-5473

4340 lbs
= 463 hp

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Summary

- **Zero-Crosswind Drag Reduction** (relative to empty cars)
  - Full: 29%; Covered Car: 43%
  - Three full-height dividers: 21%
  - Two triangular dividers: 15% & 17% (extended)
- **Wind-averaged Drag Reduction**
  - Two triangular dividers: 16% & 25% (extended)

>> 25% reduction –> 5% fuel savings (75 million gal/yr)

>> Can be retrofit by attaching to internal bracing

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Future Work

- Larger scale testing
- Optimization
  - Dividers size, shape, location
  - Operational conditions / constraints
- Full-scale validation at TTC

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Effect of Train Length
(zero crosswind)

Configuration	Cd	% difference
2-1-2	0.2753	0.0
3-1-2	0.2664	-3.2
1-1-2	0.2996	8.8
2-1-1	0.2788	1.3

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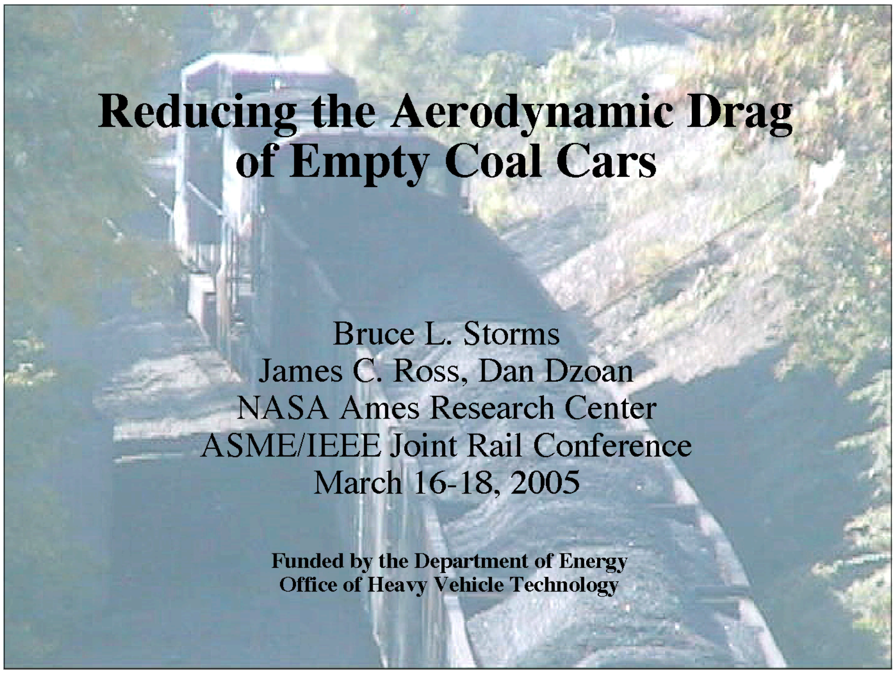

Reducing the Aerodynamic Drag
of Empty Coal Cars
Bruce L. Storms
James C. Ross, Dan Dzoan
NASA Ames Research Center
ASME/IEEE Joint Rail Conference
March 16-18, 2005
Funded by the Department of Energy
Office of Heavy Vehicle Technology

THE UNIVERSITY OF TENNESSEE
SimCenter
AT CHATTANOOGA
Computational Simulation and Design Center

GRADUATE SCHOOL OF COMPUTATIONAL ENGINEERING

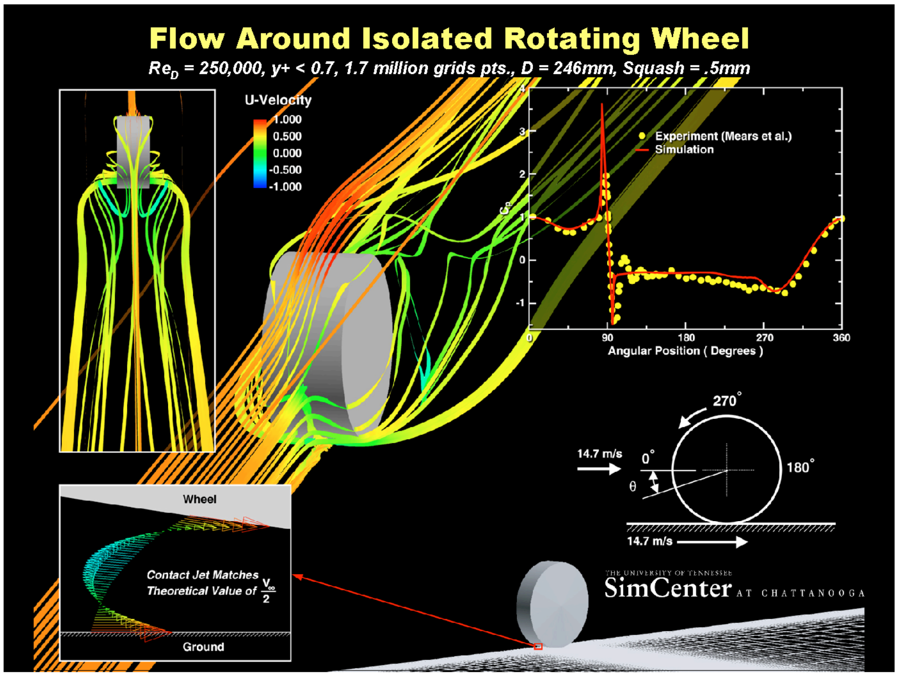
Tire Aerodynamics, Splash & Spray
Brake Cooling

Ramesh Pankajakshan

May 13, 2005

Objective

- Develop rotating wheel simulation capability
- Validate against experimental data
- Transition to full vehicle simulations


Flow Around Isolated Rotating Wheel
Re_D = 250,000, y+ < 0.7, 1.7 million grids pts., D = 246mm, Squash = .5mm
U-Velocity
1.000
0.500
0.000
-0.500
-1.000
Experiment (Mears et al.)
Simulation
C_p
Angular Position (Degrees)
14.7 m/s
0°
θ
270°
180°
14.7 m/s
Wheel
Contact Jet Matches Theoretical Value of $\frac{V_\infty}{2}$
Ground
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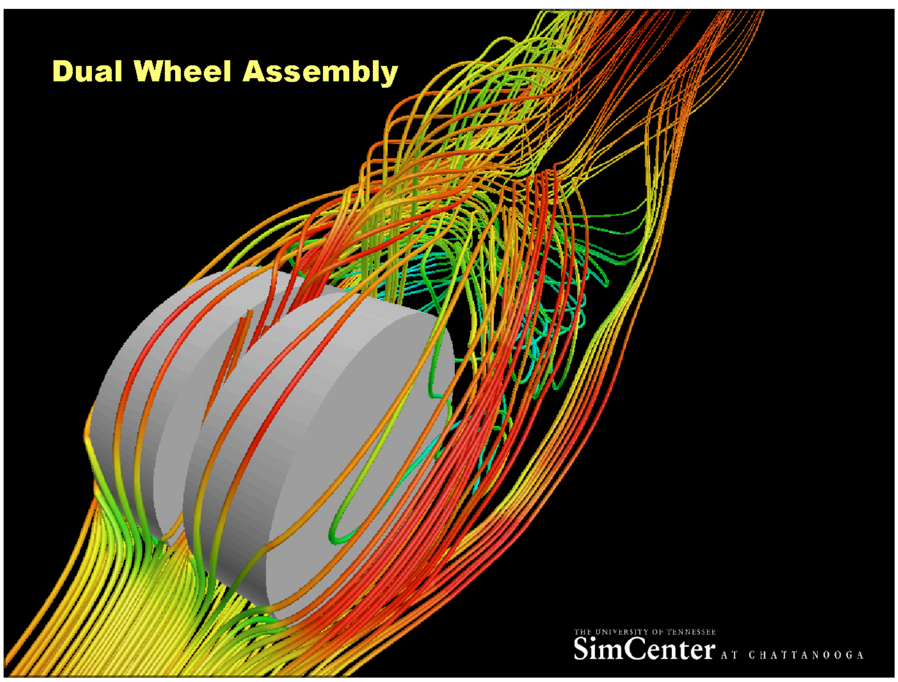
Dual Wheel Assembly
THE UNIVERSITY OF TENNESSEE
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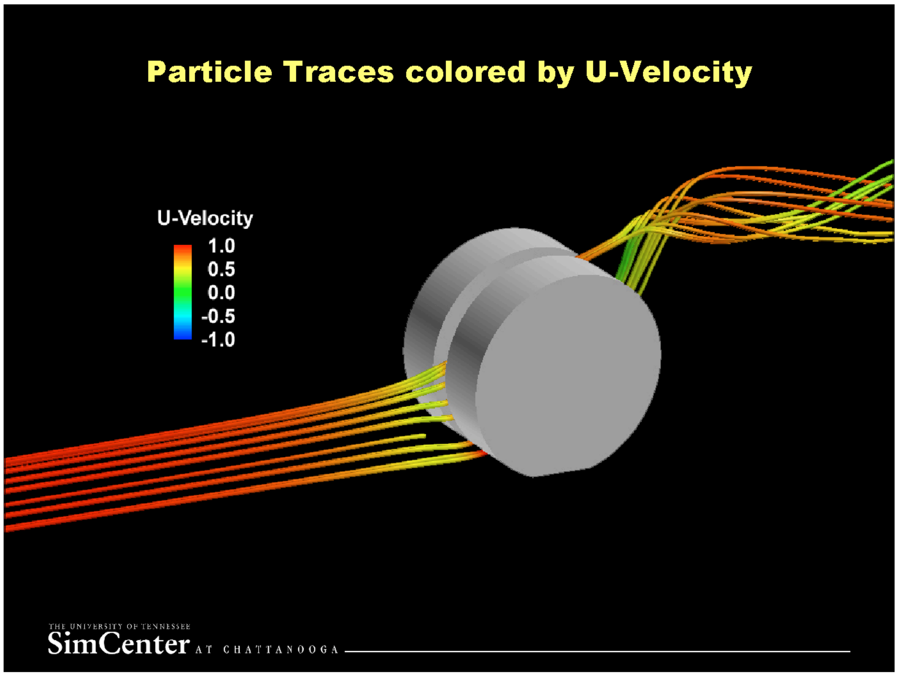
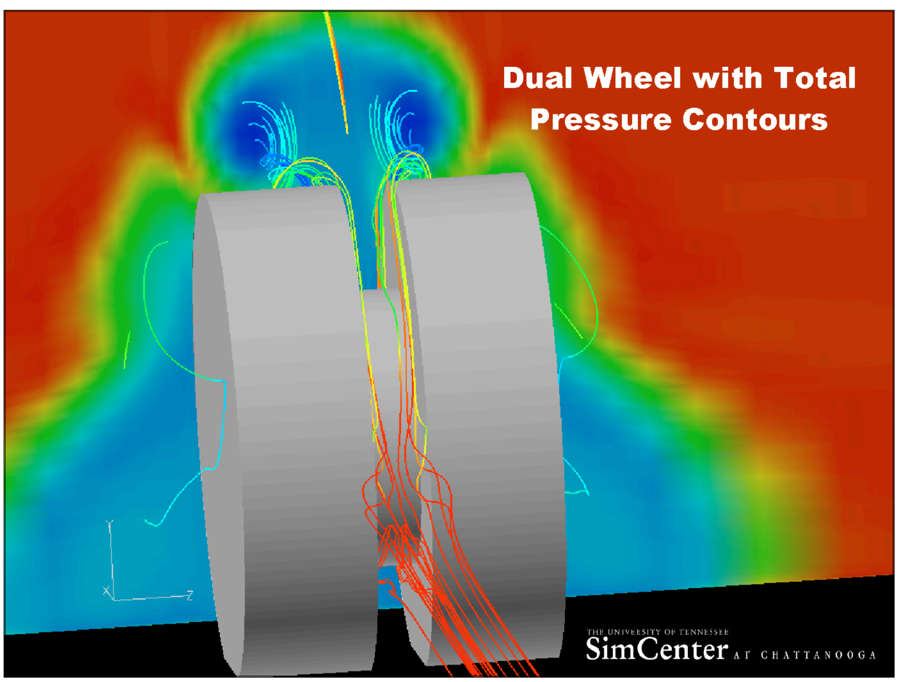

Particle Traces colored by U-Velocity
U-Velocity
1.0
0.5
0.0
-0.5
-1.0
THE UNIVERSITY OF TENNESSEE
SimCenter AT CHATTANOOGA


Dual Wheel with Total Pressure Contours
THE UNIVERSITY OF TENNESSEE
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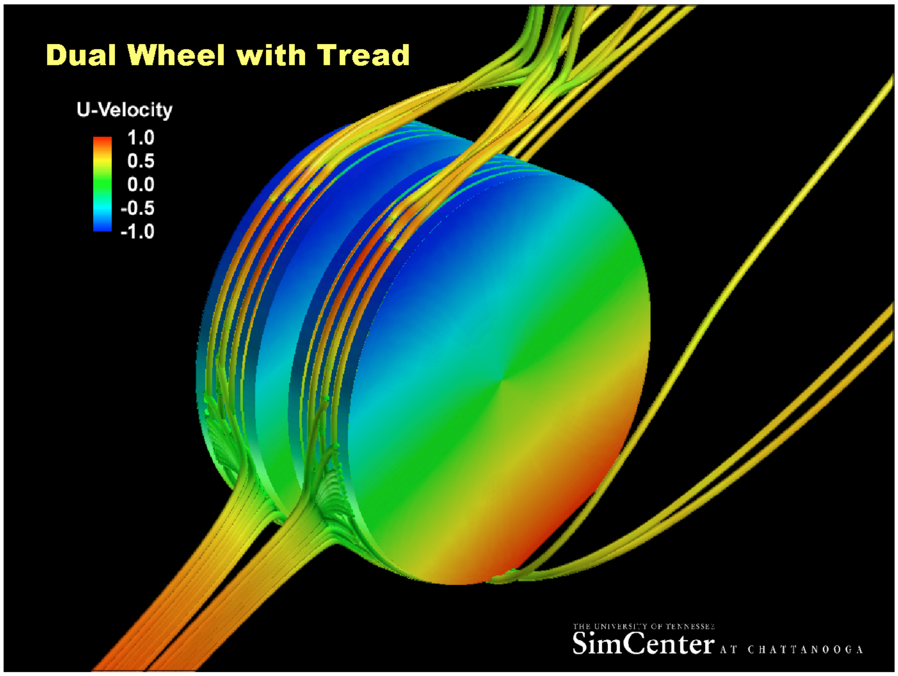
Dual Wheel with Tread
U-Velocity
1.0
0.5
0.0
-0.5
-1.0
THE UNIVERSITY OF TENNESSEE
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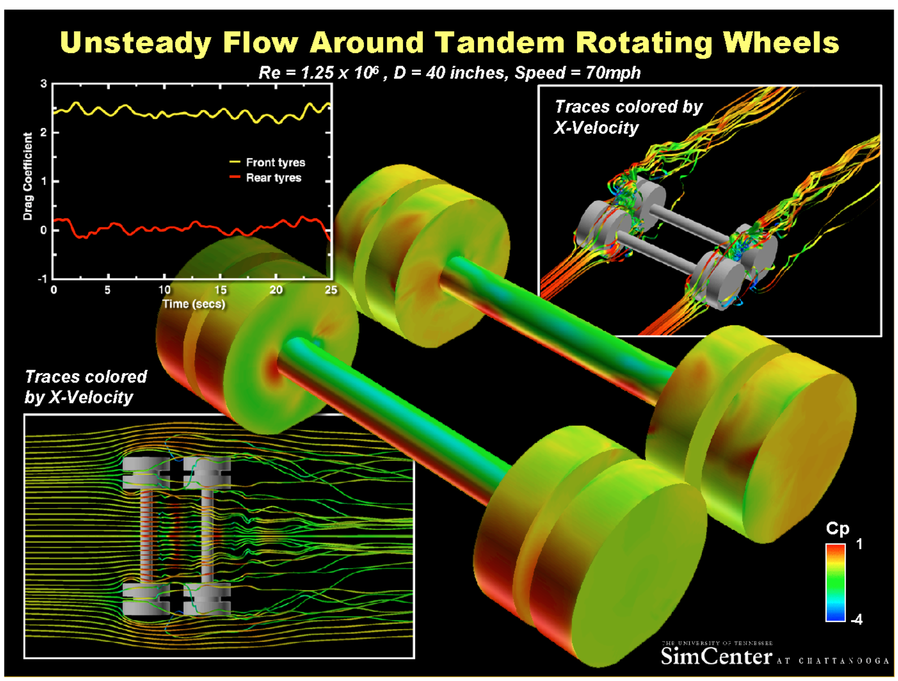
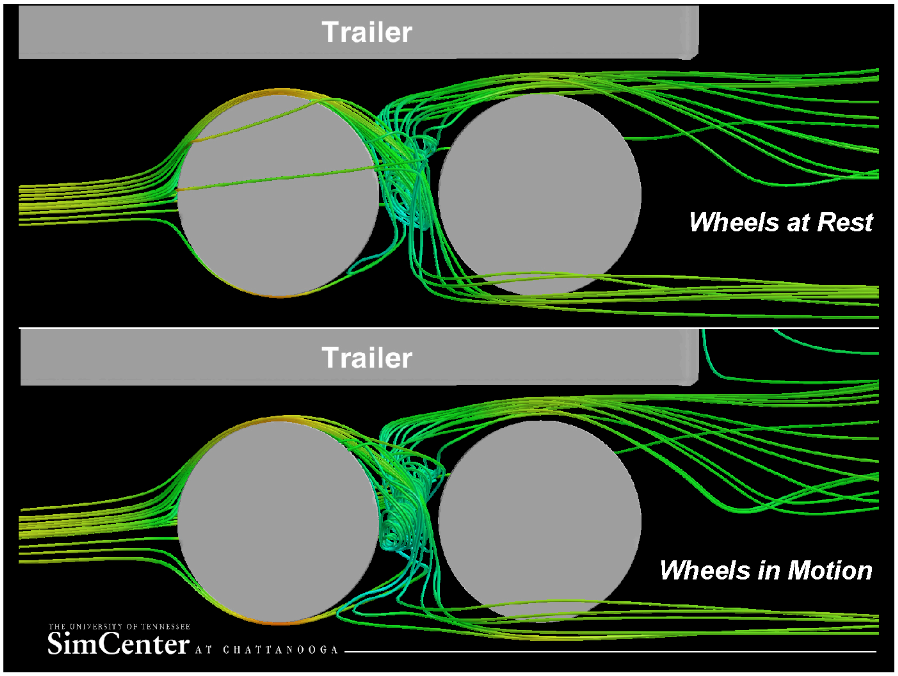

Unsteady Flow Around Tandem Rotating Wheels
Re = 1.25 x 10^6 , D = 40 inches, Speed = 70mph
Drag Coefficient
Time (secs)
Front tyres
Rear tyres
Traces colored by X-Velocity
Traces colored by X-Velocity
Cp
1
-4
THE UNIVERSITY OF TENNESSEE
SimCenter AT CHATTANOOGA



Splash & Spray

- Realistic geometry
  - Tread
  - Wheel Holes
  - Wheel Well/Trailer Underbody
  - Full Geometry

- Simulation effects
  - Large Grid Sizes
  - Relative Grid Motion
  - Large Simulation Time

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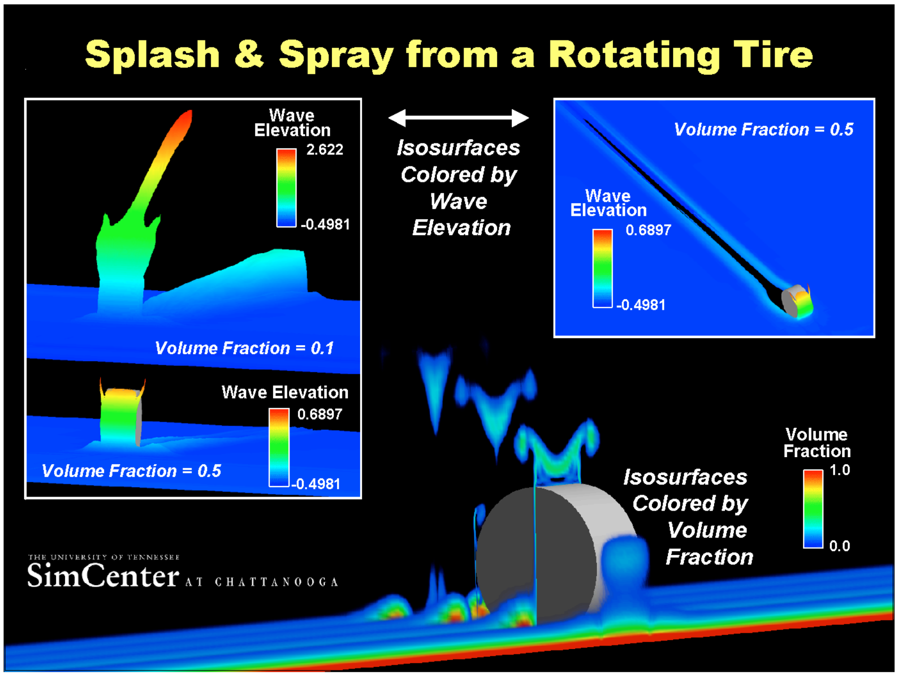
SimCenter AT CHATTANOOGA


Splash & Spray from a Rotating Tire
Wave Elevation
2.622
-0.4981
Volume Fraction = 0.1
Wave Elevation
0.6897
-0.4981
Volume Fraction = 0.5
Isosurfaces Colored by Wave Elevation
Volume Fraction = 0.5
Wave Elevation
0.6897
-0.4981
Isosurfaces Colored by Volume Fraction
Volume Fraction
1.0
0.0
THE UNIVERSITY OF TENNESSEE
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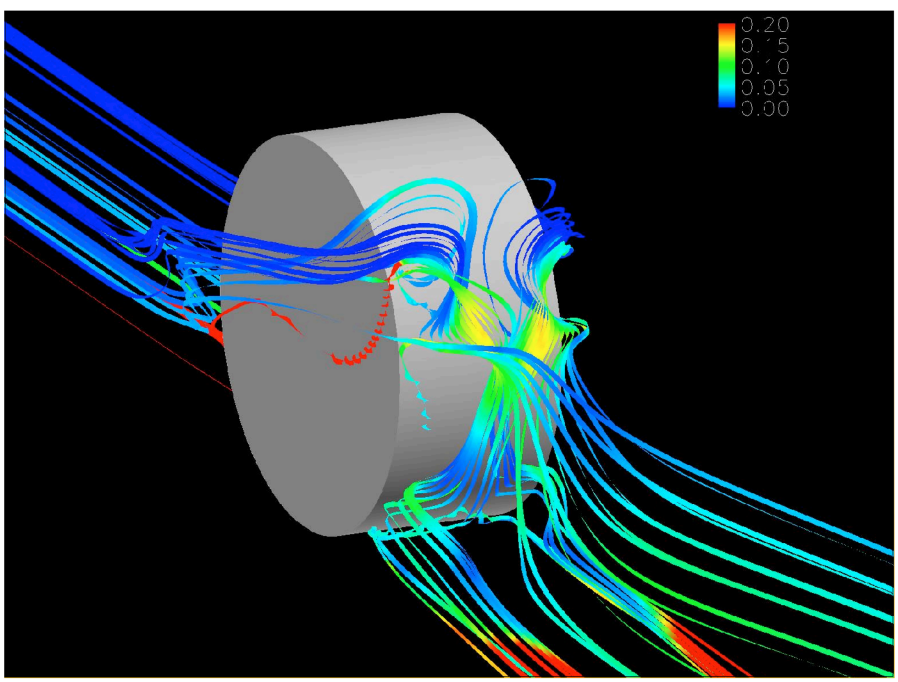
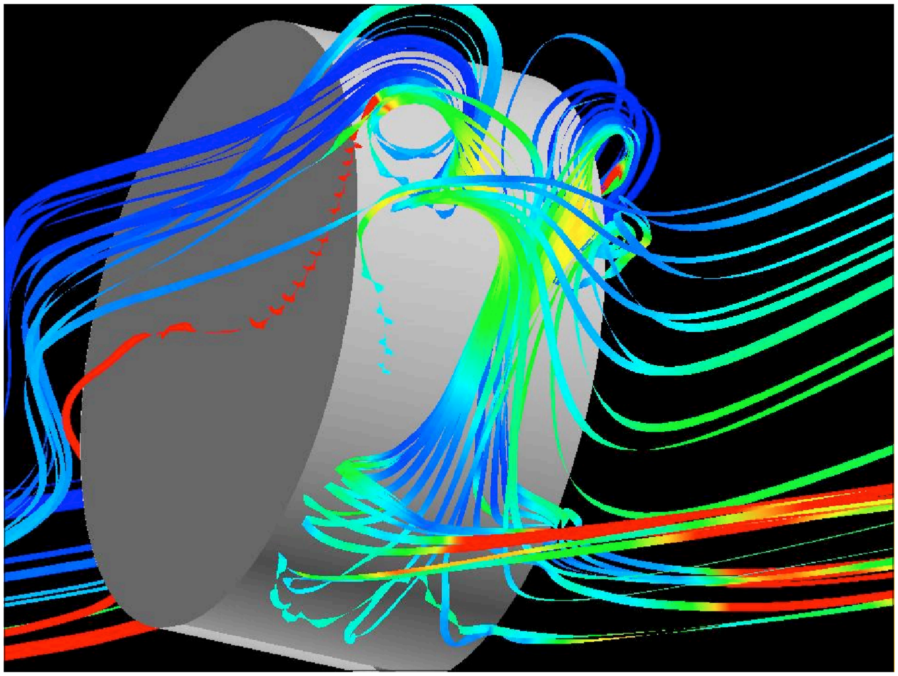

0.20
0.15
0.10
0.05
0.00



Brake Cooling

- Issues in brake cooling simulation
  - Relative Grid Motion
  - Buoyancy
  - Transition
  - Full Vehicle Simulation
  - Aero Braking Devices

Improving truck safety using computational tools

John Paschkewitz, Craig Eastwood, Jason Ortega
Lawrence Livermore National Laboratory
Heavy Vehicle Aero Consortium Meeting
May 13, 2005

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Objectives and Accomplishments

Goal: "Investigate tire aerodynamics, study influence of wheel wells, and predict brake cooling performance"

- Completed simulations of rotating cylinder and wheel (including treads & duals)
- Working on complex geometries

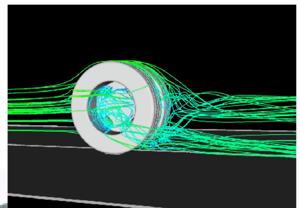
Goal: "Investigate state-of-the-art modeling capability in multi-phase flows to model splash and spray"

- Explored volume-of-fluid (VOF) methods for splash
- Completed spray simulations on realistic truck geometry, demonstrating key spray physics
- Established collaboration with Stanford Center for Turbulence Research (CTR)
  - Leveraged DOE/ASC investment to apply cutting-edge multiphase LES code (CDP) to splash & spray problem

2

Wheel and wheel well aerodynamics are essential to improving truck safety

Wheel and wheel well aerodynamics



http://www.odot.state.or.us/its/newsevents/Newsletter/news040101.htm

Brake cooling

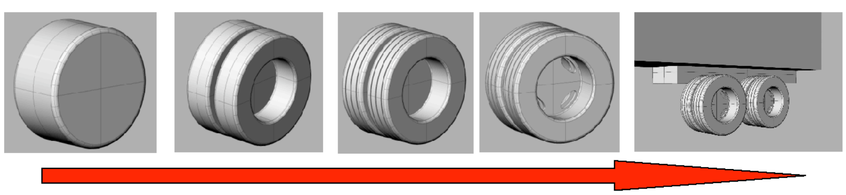
http://www.aaafoundation.org/e-news/issue6/splashspray.cfm

Splash & Spray

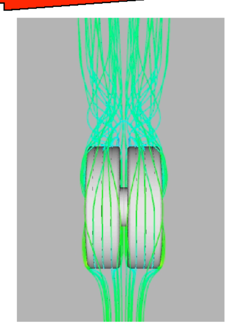
- **Focus on splash & spray**
- **Multiphase flow modeling introduces added complexity**

3

"Bottom up" approach to build confidence in wheel aerodynamics solutions



- **Using progressively more realistic models to capture wheel aerodynamics**
- **Simple models validated against available data**
- **Treads, tire shape and wheel important**
- **Meshing is challenging!**
  - **Consider immersed boundary (IB) approach when available in CDP this winter**



4

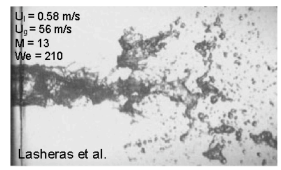
What is splash and what is spray?

Primary Atomization (splash)

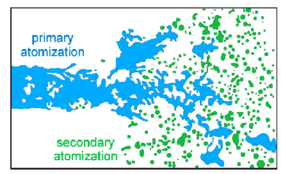
- **Initial breakup into large and small structures (ligaments/drops) close to the tire**
- **Complex interface topology of large scale coherent liquid structures**

NO rigorous models **describing primary breakup in turbulent environments**

Secondary Atomization (spray)



schematic

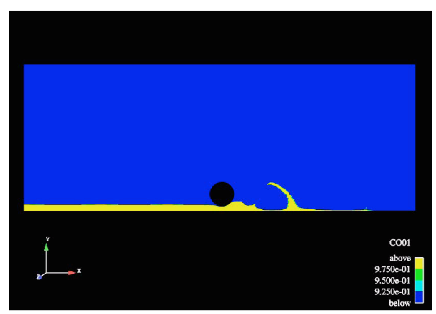


c/o Marcus Herrmann, Stanford/CTR

5

Splash modeling requires accurate interface tracking and coupling to spray

- StarCD uses the **Volume of Fluid (VOF)** approach
  - **VOF methods are well-accepted** and have good mass conservation properties
  - Solves single momentum equation for two fluids and tracks volume fraction of fluid in each cell
  - Surface tension effects accounted for using a "pseudo pressure"



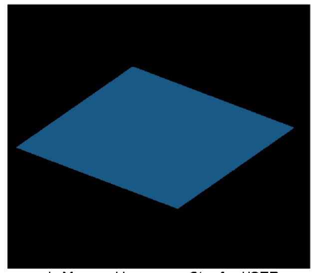
Result: 2D cylinder rotating above sheet of liquid flowing at 5 m/s

Issues:
- **Interface reconstruction is not exact**
- **Coupling to spray calculations is not straightforward**
- **Need validation data! Fred Browand, other studies**

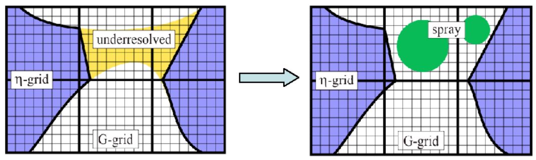
6

Looking ahead: Splash modeling with CDP

- CDP uses a **level-set** approach for interface tracking (Particle level set method (Enright, Fedkiw, Ferziger & Mitchell, 2002, *J.Comp.Phys.* 183)
- **Better interface capturing** than StarCD
- Largely DNS-focused at this time
- Developing a **novel method for coupling film-spray transition** using multiple grid methods
- Active research area at Stanford/CTR



c/o Marcus Herrmann, Stanford/CTR



Refined Level Set Grid (RLSG) method uses a coarse mesh (η-grid) and fine mesh (G-grid). Compare fluid-air interface on two grids to identify topology changes and define droplet formation events

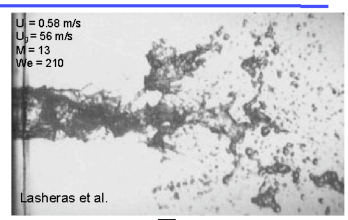
7

Spray modeling involves capturing breakup and dispersion

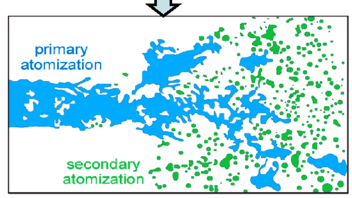
Primary Atomization (splash)

Secondary Atomization (spray)

- **Subsequent breakup into ever smaller drops forming a spray**
- **Simple geometry of small scale liquid drops (spheres) can be assumed**
- **Models for secondary breakup in turbulent environments exist (spray models)**



c/o Marcus Herrmann, Stanford/CTR



Important non-dimensional parameter:
Weber number (We) = ratio of fluid inertia (dynamic pressure) to droplet surface tension force

$$We = \frac{\rho V^2 D}{\sigma}$$

8

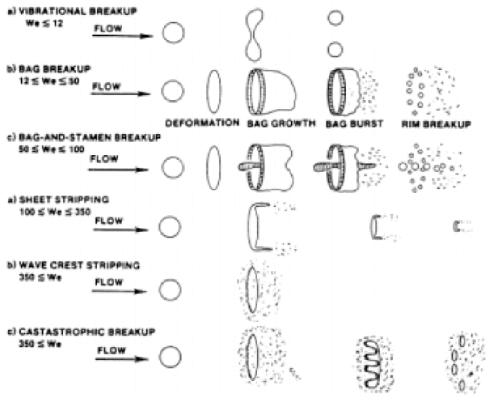
Droplet breakup mechanisms

Spray breakup models are ***empirical***

Breakup physics are complicated!

- StarCD uses several models, "best" is Pilch & Erdman model (1987)
- Drops break if We ~ O(10)

$$We = \frac{\rho V^2 D}{\sigma} \quad \frac{\text{Carrier fluid inertia}}{\text{Surface tension}}$$



From: Pilch and Erdman, Int. J. Multiphase flow, 13, p. 741-757, 1987 and http://www.aem.umn.edu/people/faculty/joseph/archive/docs/breakup99.pdf

9

Do we expect droplet breakup?

What type of breakup do we expect and what is timescale for breakup?

Consider water drops with various diameters and slip velocity (difference between drop and air velocity) of 15 m/s:

Diameter (m)	We	Mode	Breakup time
5e-2	**188**	**Sheet stripping**	**0.4 sec**
1e-2	**38**	**Bag**	**0.1 sec**
1e-3	**3.7**	**NONE**	**NONE**

Conclusions:

- Large drops will break slowly relative to time in air
  - Ballistic trajectory takes ~ 0.1 sec to hit bottom of truck
- Small drops making up spray not likely to break!
- **Breakup largely due to collisions with truck surfaces**

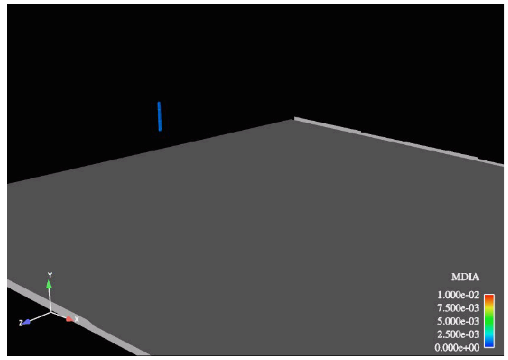
10

Droplet-surface collisions are critical and can be modeled

Collisions are essential to modeling spray production about truck

Active research area!

- Many empirical correlations
- Dry vs. wet surfaces important



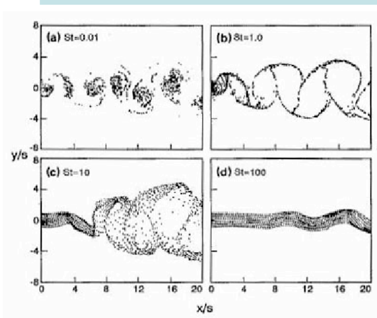
StarCD uses the Bai model (Bai & Gosman, SAE paper 950283, 1995) :

- Stochastic model that incorporates stick, spread, rebound and splash
- Assumes wetted wall (OK for truck)
- Daughter drop size/velocity depend on incident angle, droplet size and properties

11

Particle inertia impacts dispersion

- Particle inertia leads to important dynamic behavior!
- Important parameter is Stokes number (relative importance of particle to fluid inertia)
- If inertia is not too large (St < 10), see preferential concentration
  - Small particles get trapped in vortex cores
  - Larger particles get thrown towards outside of vortices



Tang et al, Phys. Fluids (1992)

$$St = \frac{\tau_P}{\tau_F} = \frac{\rho_P d_P^{\,2} H}{18\mu_C U}$$

Blue: St = 1e-3
Green: St = 0.1
Red: St =10

Dimensions and conditions:
Plane height H=2m(characteristic length)
Re = rUH/m=5100
U = 1 m/s, r=1 kg/m^3, m=1.96e-4 kg/ms

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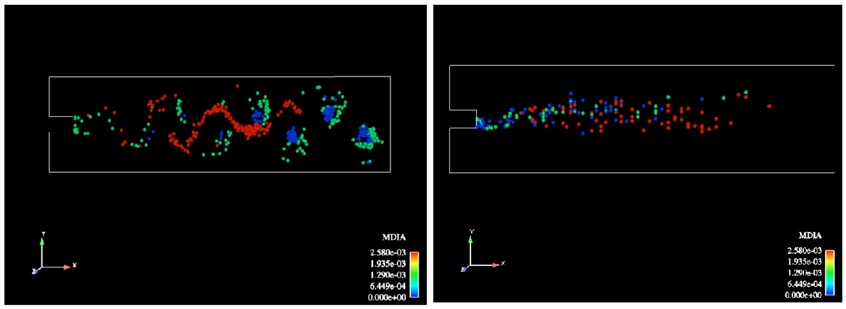
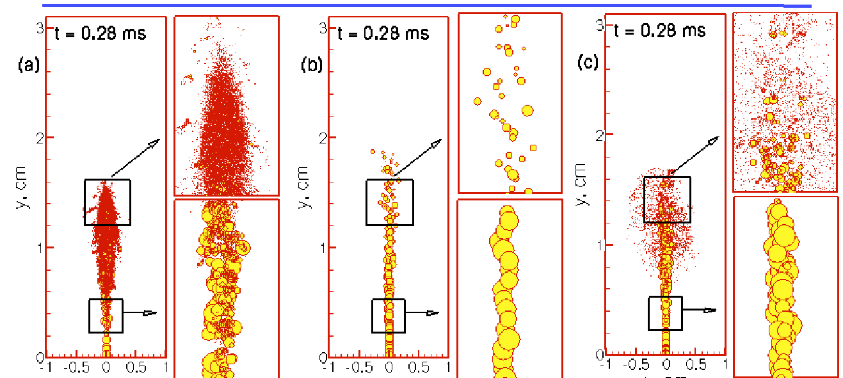
Steady-state simulations give incorrect dispersion



Unsteady RANS　　　　Steady RANS

- Droplet behavior and flow field in steady RANS framework are simply WRONG!
- MUST use unsteady RANS/LES framework to correctly capture spray dispersion behavior

Computations: Droplet, Parcels, & Hybrid Approach



c/o S.V. Apte, Stanford, Int. J. Mult. Flow, 2003

Droplets (CDP)　　Parcels (StarCD)　　Hybrid (CDP)

- *Parcels* are used to manage computational cost but can be inaccurate
- Parcel = collection of identical-sized particles with constant mass
- Breakup increases the number of particles in a parcel, NOT number of parcels

A computational model of truck spray

Details:

- Unsteady RANS, Re = 6E6, total time = 1.5 sec
- Rotating wheels
- Water droplets, uncoupled
- Injection velocity: 20-30 m/s
- 4.5L/s at 18 injectors
- 1000 parcels/sec
- 3 injection diameters
- Turbulent dispersion model
- Bai collision model
- Pilch & Erdman breakup

Findings:

- **No breakups observed in flow**
- **See drops “size segregate” in vortex motions**
- **Large velocities (30 m/s) required for small drops to get entrained in flow**
- **Drops in spray are approximately 100 microns in diameter**
- **Rich dynamics due to collision model around trailer wheels – film, breakage**

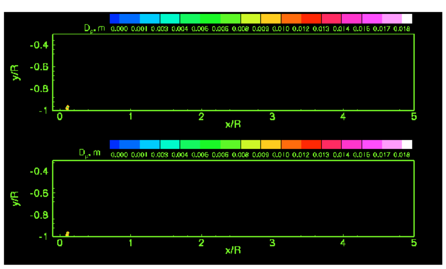
Looking ahead:

- **Need much clearer idea of droplet sizes and velocities making up spray! (INLET CONDITIONS?)**
- **Validation data is needed**

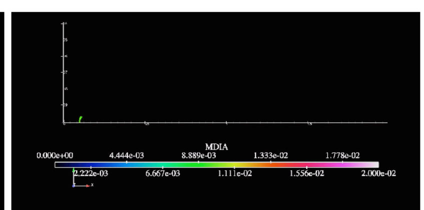
15

Looking ahead- spray modeling using LES/DES

Cross-flow atomization in turbulent channel flow at Re=10000
Jet-A droplets, injection velocity = 0.18 m/s, centerline velocity ~ 18 m/s



LES without (top) and with (bottom) coalescence



Unsteady RANS with coalescence

- Accurate spray calculation and visibility estimates require a LES/DES approach!
- Combination of parcels and URANS phase averaging removes important interactions with flow structures
- Working with Stanford CTR to model spray using CDP

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Conclusions

- LLNL has capability to investigate splash, spray and brake cooling
  - Completed detailed spray calculations
  - Preliminary splash calculations
  - Moving into brake cooling
- Generating database of wheel aerodynamics results central to all parts of problem
- Splash tools being investigated
  - VOF and level set using CDP
  - Interface tracking and coupling to spray challenging!
- Spray simulations in progress
  - Lagrangian particle tracking with URANS, parcels
  - Finite mass, collision models important
  - Need LES/DES to capture “billowing” and accurately estimate visibility reduction
- Need validation data for all parts of problem!

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Action Items

Technical

Get paper on measure of aero from tire load SAE 92-0346 (LLNL)
Duals vs singles SAE II test data from Bob E (Jules)
Check Kenworth/PACCAR website paper with recommendation on devices (LLNL)
Look at hula skirts - CFD-porous flexing plate, test- NRC. NASA (NASA)
Consider benefits for reducing drag for hybrid vehicles- UPS (USC, LLNL)
Address underhood cooling with aero-white paper, CRADA (NASA, LLNL)
Consider open grate at base of gap (LLNL)
Will baseflap and wedge counteract (LLNL)
Can flow be excited to improve baseflaps, effect of different flap angles (LLNL)
S&S with baseflaps and visibility of brake lights (LLNL)
Evaluate singularity points on rotating tire (UTC)

Action Items

Administrative

Gather all viewgraphs from meeting (ALL send to Rose)
SAE Conf Chicago in Nov
    Papers (ALL), Panel (Kambiz), Invite (Rose)
    Meeting with fleet owners, ATA (Rose)
Contribute to 21CTP white paper on aero
    Attend, present at aero merit review in Sept (Rose)
Join Marty F. at an ATA, TMC, or TMA committee meeting (Rose)
Sharing of DOE industry Consortium test plan (Sid)
Construct industry collaborative proposals to DOE's 2007 RFP (ALL)
CRADA on wheel aero and S&S (USC, LLNL)
Industry insentives – talk to 21CTP, Ken Howden (Sid)
Visit other big fleet operators, Fedex, UPS (LLNL, USC, NASA, UTC)
Find the product engineers or decide if need national labs to design (LLNL)
Ask NRC to test effectiveness of devices for braking (LLNL)
Meet with rail companies, car manuf., power companies (NASA)
Meeting with DOT & Bill Knee (Sid)
Meeting with Vic Suski (Sid)
SOWs with conf calls, completed by June (Rose)
Suggest people for ECI meeting to Dave W. (ALL)